KahleAcoustics

ALTIA
Acoustique
Audio-Visuel

**Philharmonie de Paris**

# ACOUSTIC BRIEF

Section on

Concert Hall

only

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# INTRODUCTION

The project of the Philarmonie de Paris consists of a grand auditorium, two large rehearsal rooms accessible to the public, a set of rehearsal rooms for several ensembles in permanent residency, offices, a hall and public foyers, an education and musical initiation centre, and an exhibition room.

From an acoustic point of view, the grand auditorium - with a planned capacity of 2400 seats - is obviously the most important part of the project. The auditorium will in the first place be designed to favour and resound the symphonic repertoire, and for this use an excellent acoustic quality is essential.. The auditorium should – in good acoustic conditions - equally host recitals, chamber music and opera (in orchestral version) as well as other types of musical expression such as jazz, world music, amplified and/or spatially manipulated contemporary music.

The ambition is to meet the highest possible standards in acoustic quality while allowing for a creative concept both architecturally and acoustically. The *maître d'ouvrage* (client) clearly emphasizes his desire to build an enveloping and flexible auditorium, particularly with respect to the use and location of the stage, with an important proximity between the stage and the audience and a strong intimacy between the musicians and the audience.

It is obvious that the acoustics of the other spaces of the complex must be of high standards both in terms of room acoustics and sound insulation between these spaces and with respect to external noise.

This document is structured as follows:

- A study of the topology of concert halls which points out the differences between the various types and shapes of halls, to initiate the discussion on the concept and to highlight the key acoustic elements of a great auditorium.

- A chapter detailing the design criteria for the auditorium, both architectural criteria to be respected in order to meet the desired acoustic quality, and purely acoustical criteria. Tables at the end of this chapter summarise the various architectural and acoustic criteria to be met.

- A chapter on the subjective parameters and objective criteria sought for the design of the grand auditorium.

- A chapter concerning the other rooms of the complex, in particular the rehearsal rooms, control rooms and recording studios, public foyers, offices etc. Acoustic insulation and vibration isolation are also discussed.

- Appendices presenting detailed tables with the expected performance of each space in the building, and the definitions of the acoustic criteria used in this document.

The acoustic success of this project will depend to an important degree on the initial architectural, technical and financial choices. This particular aspect remains open to dialogue between the acousticians of the design team and those of the client so that if necessary the objectives can be readjusted to better fit the architectural concepts proposed.

The success also depends on the acoustic design - in terms of sound and vibration isolation, shapes and volumes, materials and surfaces, acoustic variability - and on good collaboration within the design team. The brief "Acoustics" is NOT a separate task but must be embedded with all the architectural and technical tasks and for this reason, we recommend to every member of the design team to read this document. We have intended to adopt a writing style that is relatively clear to layman readers, while staying sufficiently precise for acoustic specialists.

# CHAPTER 1. TYPOLOGY OF CONCERT HALLS

In order to provide to the design team a basis for reflection, and to establish a common language, it is proposed to discuss and analyse the different types and shapes of concert halls in this chapter.

It is obvious that this topology is not exhaustive and that the boundaries between the different types of halls are not always well defined – to give one example, a vineyard hall can also be inscribed inside a shoebox hall.

This description, associated with the next two chapters, will also help to understand how the different types of halls work acoustically.

## 1.1. The "shoebox" concert hall

Firstly, it is interesting to note that the shoebox shape, typically associated with concert halls in the minds of many, is closely related to the history of the development of these rooms.

The shoebox concept has historically developed, from rehearsal and ballrooms of royal courts on the one hand, and from churches - in particular protestant – on the other hand. In the latter spaces, speech intelligibility was more important and the acoustic quality is often similar to that of concert halls, as we know them in our times.

Ballrooms were usually rectangular, often with very high ceilings - both for the quality of the air and to impress the guests. The materials were essentially reflective from an acoustic point of view (timber floor, plaster and/or marble, some windows and perhaps a few tapestries) and exhibited many ornamentations. Sometimes, these rooms also contained small galleries and balustrades. Regarding their shape, these rooms were either square or elongated, and therefore already of the shoebox type.

Also, a significant part of the music repertoire still played today was specifically composed for these particular rooms and their specific acoustic. To give some examples: Haydn's early and middle symphonies (for Prince Esterhazy's castles in Vienna and in Eisenstadt), Bach's compositions (Weimar and Köthen) and the quartets and first symphonies from Beethoven for the Rasumofsky Palace.

The protestant churches, which are of particular interest here, are rectangular (rather elongated) with great ceiling heights. Often galleries or balconies were built to accommodate musicians, choirs or audience. These churches were often acoustically treated to improve speech intelligibility, despite the ceiling height. Part of the classical repertoire has been composed for these churches.

Less relevant here are catholic churches and cathedrals. Their important volume and ample acoustics have also led to a specific musical repertoire requiring greater reverberation than that of a typical concert hall. It remains, however, interesting to note that these musical compositions (e.g. early music, masses and requiems) have for a long time been exclusively performed in churches and cathedrals. This type of compositions has, since then, been deconsecrated and introduced to concert halls. Therefore, the requirements of this music – particularly the extension of the reverberation time above the generally required 2 seconds – are also to be considered for the design of the Paris Philharmonie.

What is characteristic of most shoebox halls – and particularly the historical ones – is their "fullness" of sound, the importance of the room effect and the sensation of being surrounded by sound. For small shoeboxes without balconies this is not really surprising as one can compare them to "extended bathrooms" where (luckily) a lot of ornamentations mitigate the undesirable effects of flat and reflective parallel walls. The sound generated by the instruments, in addition to the direct sound, propagates to the ceiling and is reflected back toward the audience after a relatively long trajectory (and thus a long time delay). Apart from the direct sound, there is little early acoustic energy and early reflections, while the late energy and the feeling of a late sound field are dominant. This works quite well for small halls with moderate ceiling heights but not for large rooms: the lack of early energy becomes noticeable and the presence of the source, and the definition and speech intelligibility become too small. (This is typically the case in e.g. catholic churches and cathedrals, or shoebox halls without balconies.)

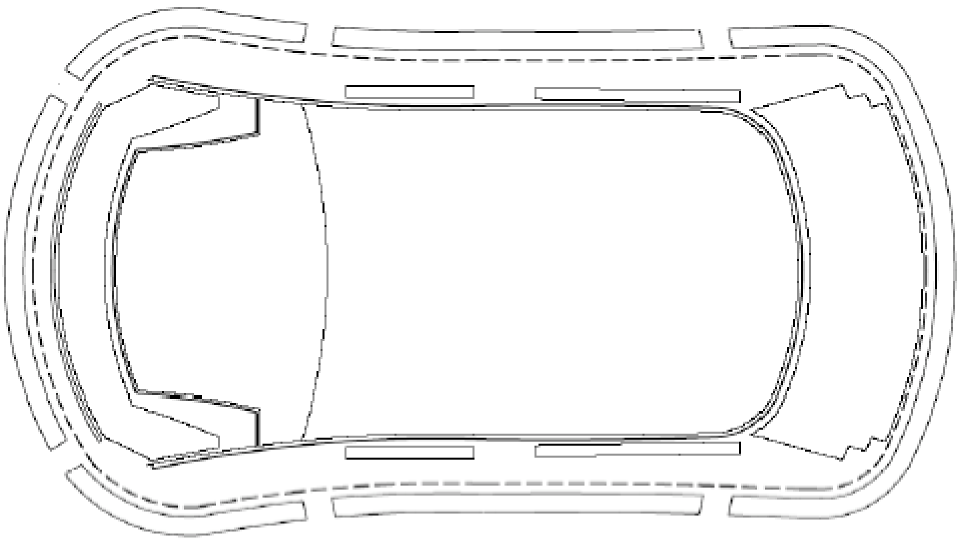
The lateral balconies and more particularly their lower surface play a major role in the acoustics of shoebox concert halls. In most large halls, the seats on the ground floor receive less early reflections from the ceiling than from the horizontal soffits of the lateral and back balconies. Above the highest balcony, there is generally sufficient ceiling height to allow build-up of reverberation between the lateral walls. The area below the highest balcony is essentially used to generate reflections, increasing the early energy and therefore the source presence, listening precision and intelligibility.

It should be noted that there is a limit to the ceiling height: the echo corresponding to a distance of 17m (return path of 34m or 100ms delay). A ceiling height of 17m above the stage is detrimental to the listening comfort of the musicians themselves. For rooms of which the ceiling height exceeds 17m, one must imperatively introduce acoustic reflectors or a continuous ceiling (canopy type) above the stage and above the front rows of the stalls.

Another limitation for shoebox halls has already been mentioned: ornamentations or other elements are essential to avoid the undesirable effects of reflective parallel walls that colour the sound and generate flutter echoes between the walls. In the 19$^{th}$ century, the ornamentations were an integral part of the architectural expression. Contemporary architecture addresses these limitations by using contemporary sculptures and 3D patterns, by using wall profiles and finishes that – at least locally - disturb the parallelism of the hall. This “anti-parallelism” treatment adds what is commonly referred to in acoustics as “diffusion”, leading to a wider distribution of reflections – as the reflected wave is wider than the incident wave.

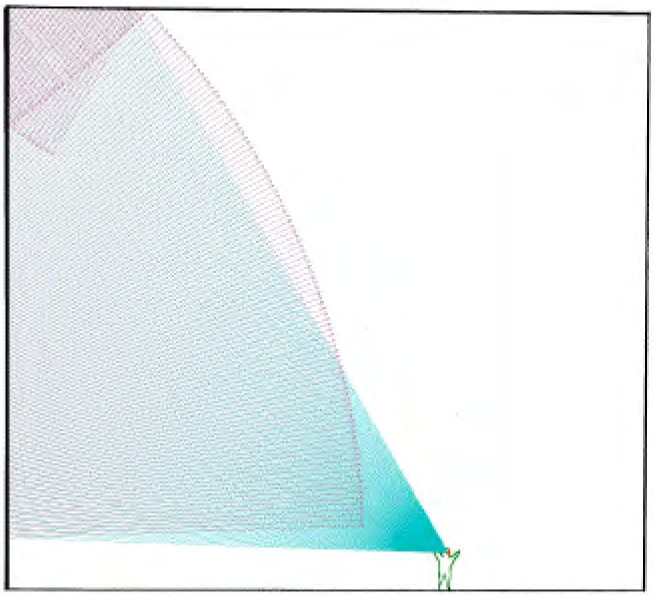
Certain studies of the acoustic quality of existing halls have found that the properties of acoustic diffusion – or the average ability of the treatment to diffuse sound – are the most important criteria to define the quality of a shoebox room.

**Example of a shoebox hall.**

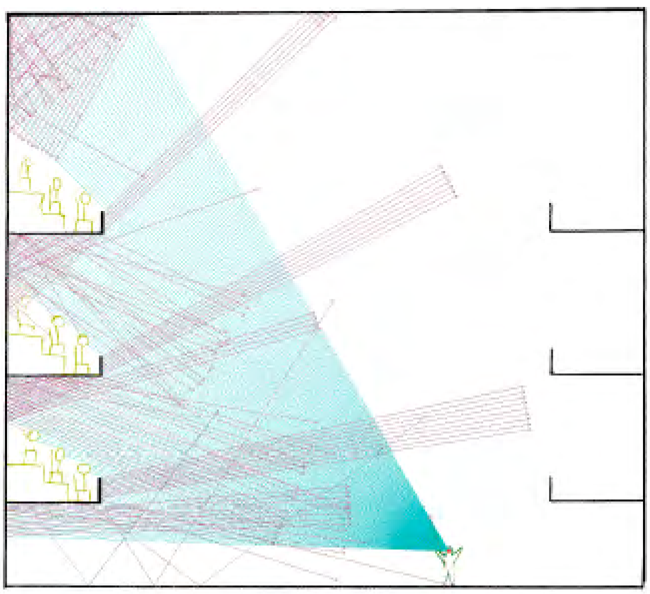


*Typical for a shoebox hall are the rectangular shape (often elongated), great ceiling height, and often the existence of galleries and balconies for the musicians or audience. Distortion and patterns (balconies, columns, niches and/or other elements) are essential to avoid the detrimental effects of parallel reflective walls, i.e. coloration and standing waves).*

**Illustration of the acoustic role of the balconies: simulation of the rays' trajectories in 2D.**
**The blue lines represent the incident rays; the purple and red lines represent the reflected rays (respectively 1st and higher order).**



*When there are no balconies, the rays are reflected at the ceiling of the room. For a relatively large room, these reflections can reach the listener with a significant time delay. There are much less early reflections, responsible for the clarity and the feeling of envelopment.*



*For the stalls seats, the lower surfaces of the balconies generate early reflections. Above the highest balcony, there is generally enough ceiling height for the reverberation to be developed between the lateral walls. The area below the highest balcony is essentially used to generate reflections, increasing the early energy and therefore the presence of the sources and intelligibility.*

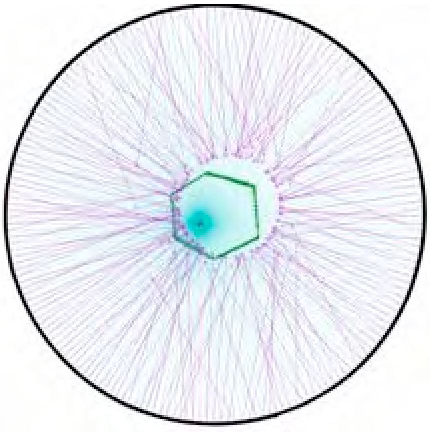
## 1.2. The vineyard concert hall

The typical model of a vineyard hall is the Berliner Philharmonie (Berlin Philharmony). It is interesting to note that the concept of vineyard halls has been developed by Lothar Cremer, the acoustician for this hall, as a response to architect Hans Scharoun's wishes to locate the orchestra as close as possible to the centre of the room and to surround it on all sides by the audience. The original concept of Scharoun was to have a completely circular hall with a shape close to an amphitheatre where the orchestra director would be standing exactly at the centre of the circle, under a dome shaped ceiling – an acoustically very dangerous concept as this geometry is prone to serious acoustic focusing. The principle behind Scharoun's concept was to position the orchestra as close as possible to the centre and thus create the most "democratic" hall. To respect the fundamental rules of acoustics, Cremer suggested a ceiling with a tent shape rather than a dome and to break up the symmetry of the hall by using convex curves. He replaced the concave curves, which tend to focus sound, with convex curves, which diffuse sound. The idea of a central orchestra was kept.

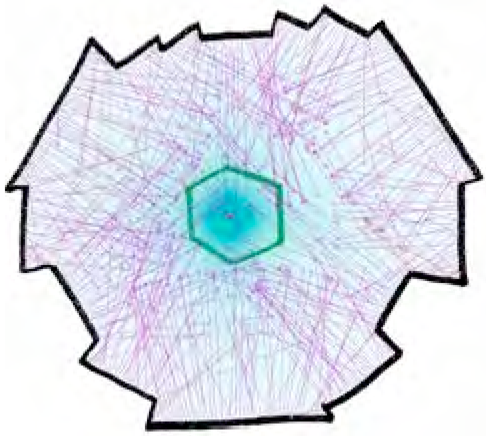
Also, the fact that the audience is located behind and to the sides of the stage, combined with the absence of a balcony has resulted in a room width that is much bigger than that of shoebox halls, and clearly wider than what is acoustically acceptable without having to introduce compensating elements. The latter elements, consisting of large wall sections, or partial walls creating "vineyard terraces", helped to reduce the apparent width of the hall and create acoustic reflections, leading to the concept of the vineyard concert hall.

It is very important to realise that the partial walls are not the only elements that guarantee the acoustic quality of such halls. The surface area of these walls is often insufficient to provide the necessary reflections to cover the entire audience. Other elements play an important role, such as the shape of the ceiling, which must be designed to allow a homogeneous distribution of the reflections over the entire hall and a sufficient acoustic volume above the musicians. In particular, the presence of acoustic reflectors above the stage can, if an appropriate profile is chosen, generate enough early reflections for the audience in front of the stage, for the musicians, as well as for the audience located behind the orchestra.

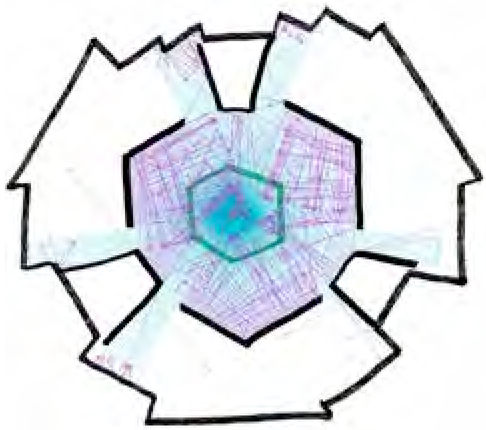
**How a vineyard concert hall works: schematics of two-dimensional sound ray trajectories.**



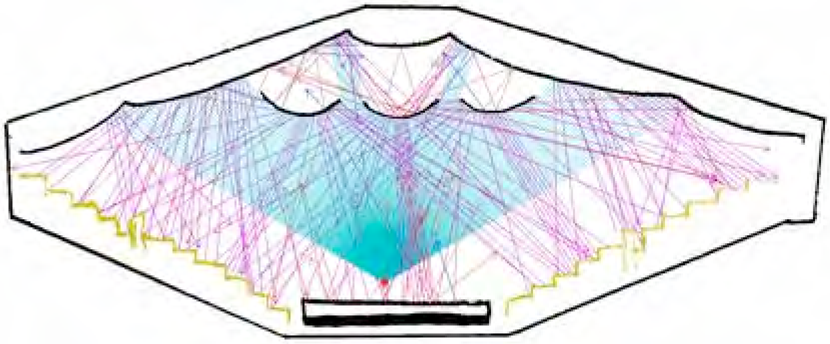
*The circular shape is detrimental and generates zones of acoustic focusing, depending on the position of the source.*



*It is necessary to break up this circular shape to diversify the directions of* the *reflections.*



*Depending on the capacity of the hall, the basic shape can generate important distances between the central stage and the walls, leading to a lack of early energy for the rows close to the stage. Adding partial walls (of partial height) help creating these early reflections in the central area of the hall.*



*The shape of the ceiling must be designed to allow a homogeneous distribution of the early reflections over the entire hall and to guarantee a sufficient acoustic volume above the musicians*

## 1.3. The early reflection design concert hall

The term "early reflection design hall" is not, *a priori*, a well-defined term as in all large concert halls, the early reflections and their temporal and spatial distribution must be optimised.

Two particular types of concert halls can be distinguished in this category.

Firstly, at the early stages of the science of acoustics (parallel with the development of loudspeakers), the aim was to optimise the projection of sound from sources towards the public. The idea was to strengthen the sound from the sources by using early and directed reflections but also to reduce the room effect - partially or as much as possible). The aim was to be able to listen to the sound sources without too much detrimental effect from the room. For loudspeaker listening, "high fidelity" and other "optimised listening rooms" were built, particularly in the US, sometimes with a capacity of several hundreds of seats, resulting in an acoustic as dry and absent as possible.

In this theory, acousticians did not consider (or did not yet know) that the feeling of space and aural envelopment – and thus the need for the listener to hear the room as well as the sources – is extremely important in the appreciation of the acoustic quality. Most high-fidelity rooms have been destroyed or transformed using more reflecting surface finishes. Also, early experiments with artificial reverberation systems were carried out in such rooms.

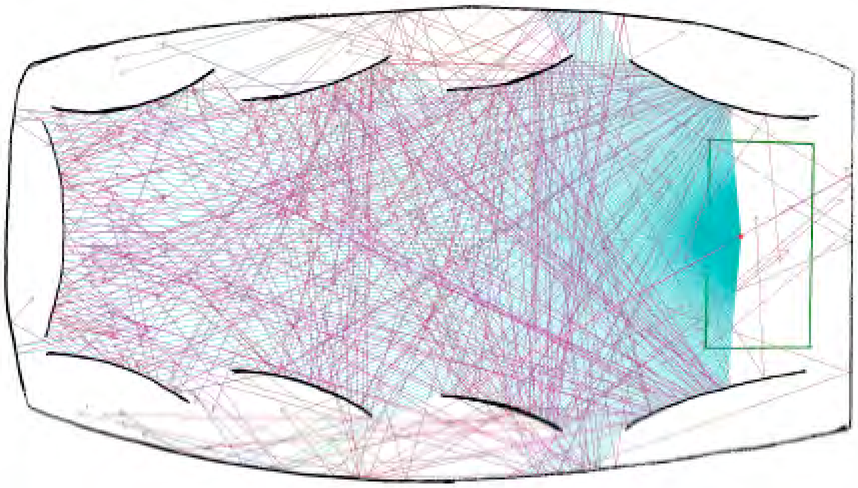
The listener's subjective need for a significant and audible response of the room, and more particularly its lateral response - discovered in the 1960s - will be described in more details in the chapter on subjective and objective parameters. The ear (and the brain) wants to both hear and follow the source (subjective perception of the presence of the source), and hear and discover the hall, the environment in which the listener is present (subjective perception of the presence of the room). The lateral incidence of early and late reflections increases the difference of signals reaching the two ears and contributes to the feeling of space and immersion in the acoustic and musical environment.

Secondly, following the discovery of the importance of the spatial effect and lateral reflections, several halls have been designed and called "optimised early reflection halls". To guarantee a good source presence in halls of large dimensions (more than 2000 seats), reflectors are installed and orientated/optimised so that useful early reflections can be generated for every seat.

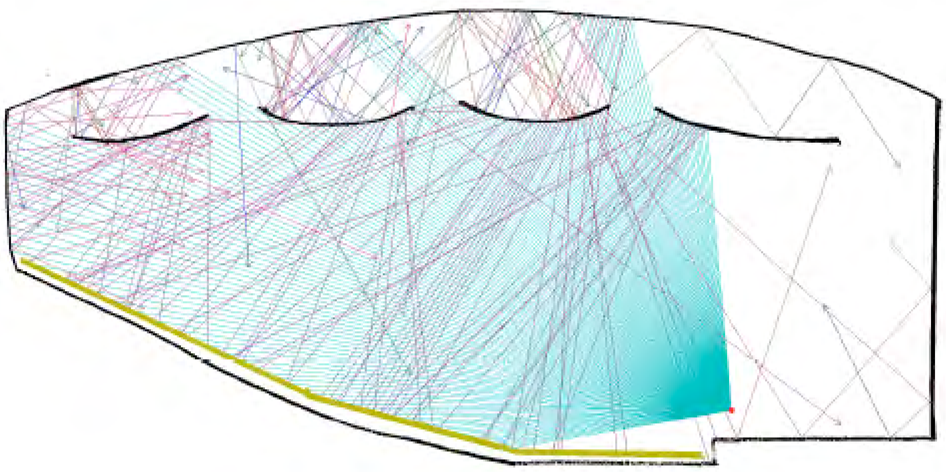
To increase the feeling of aural envelopment, the reflectors are orientated so that they create lateral reflections rather than frontal ones. Moreover, to increase the homogeneity of the distribution of these reflections and to increase the acoustic diffusion, the reflectors can take the shape of acoustic diffusers, according to the concept of quadratic residue diffusers (QRD) developed by Manfred Schroeder.

However, the set of reflectors does not create a separation between the inside and the outside of the hall - they are not the walls of the hall - but are installed within the acoustic volume of the room. The reflectors ensure a good projection between the sources and the audience and a good presence of those sources, while the volume of the room allows for a relatively long reverberation time and sufficient presence of the room and of the late sound field. Otherwise, the late sound field will often be masked by the early reflections.

**Schematisation of an "optimised early reflection hall": simulation of the rays' two-dimensional trajectories.**



*The reflectors ensure a good projection between the sources and the audience and a good presence of those sources, while the volume of the room allows for a relatively long reverberation time and sufficient presence of the room and of the late sound field.*



*The ceiling must be relatively high to ensure sufficient acoustic volume. The ceiling reflectors generate enough early reflections for good clarity and intelligibility in all locations of the hall.*

## 1.4. The arena and amphitheatre concert hall

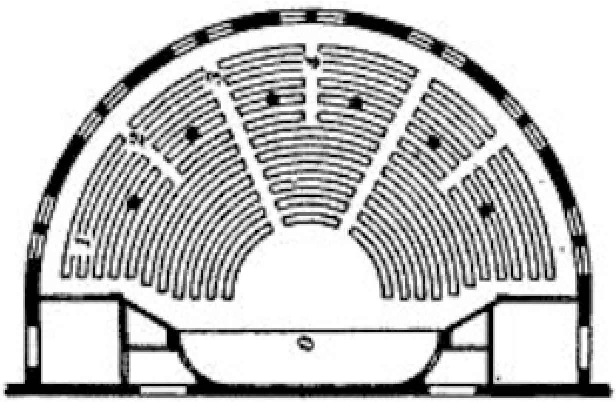
The arena halls and amphitheatres have been developed from the arenas and theatres of the antiquity. This shape works very well acoustically for theatre and speech: the distance between the sources and the listeners is minimised, the direct sound has sufficient energy (particularly if the row profile follows the logarithmic curve raising the rows as they get further from the stage) and a reflective wall is included behind the stage (“choir”). However, this shape creates acoustic problems for music and it is necessary to increase the reverberation and the room effect by closing off the acoustic volume.

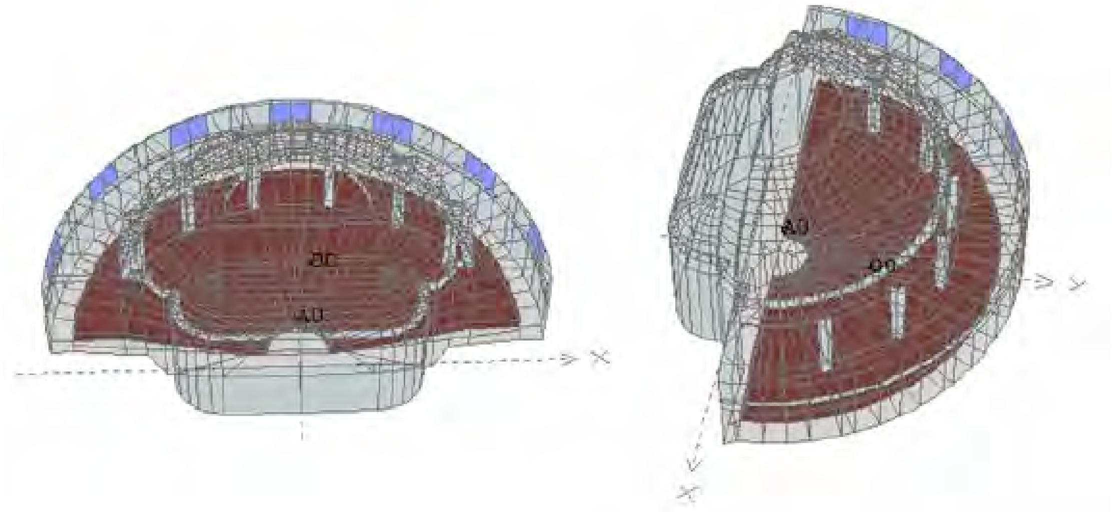
A circle – and consequently a sphere – is a geometry that does not favour the creation of a homogeneous sound field. For a source located at the centre of the sphere, there are only reflections along a diameter of the sphere and therefore no lateral reflections for receivers not located at the centre. A circle favours the energy transmission from a source to a receiving point located at the same distance from the centre of the circle - whispering galleries are an example of this – but does not favour the energy transmission from a source to a receiving point located at different distances from the centre.

To make an arena shaped hall work, one needs to introduce acoustic elements (strong acoustic diffusion or partial absorption) on the curved walls in order to “break up” the concave shape that generates focusing and to add reflective surfaces inside the volume to obtain a better distribution of the acoustic energy. One can, for example, surround the audience by a large corridor so that the sound does not reach the external concave (and therefore focusing) walls. Additionally, acoustic reflectors covering part of the stage and the audience can be installed for a better energy distribution.

In summary, the difficulty of this type of hall is first to avoid focusing and then to guarantee a sufficiently homogeneous acoustic throughout the hall, because the acoustic quality remains too often quite different for the seats close to the stage and those further up.

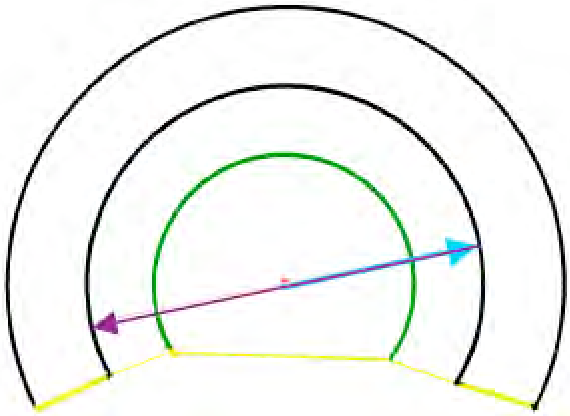
**Example of an arena hall**



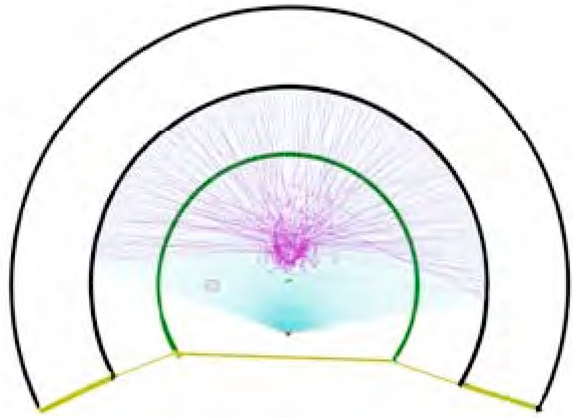



*To make an arena shaped hall work, one needs to introduce acoustic elements (strong acoustic diffusion or partial absorption) on the curved walls in order to "break up" the concave shape that generates focusing and to add reflective surfaces inside the volume to obtain a better distribution of the acoustic energy.*

**Acoustic effect of the arena shape: simulation of the two-dimensional ray trajectories.**



*For a source located at the centre of the sphere, there are only reflections along a diameter of the sphere and therefore no lateral reflections for receivers not located at the centre.*



*A circle favours the energy transmission from a source to a receiving point located at the same distance from the centre of the circle.*

## 1.5. The fan-shaped concert hall

A type of hall to avoid from an acoustic point of view is the fan-shaped hall. The advantage of such shape is that it maximises the capacity for a relatively short distance to the back of the stage while conserving an acceptable angle of view (sightlines). It is therefore not a surprise that fan-shaped halls are often used as multi-purpose halls, destined to host operas and concerts. They have mostly been built after WWII and an important number of them can be found in US.

When these halls were constructed, the notion of acoustic variability was not yet sufficiently developed. The acousticians were concentrating on the "mean reverberation time", which is a compromise between the optimum reverberation time for classical concerts and that for opera. Also, the importance of lateral reflections had not yet been discovered.

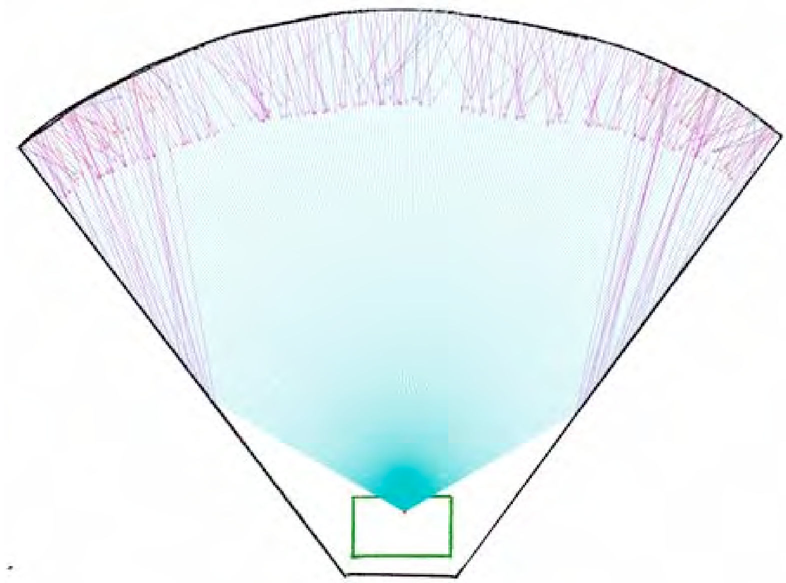
The reflections of the lateral walls – if any – are directed toward the back of the room while the front and middle areas do not benefit from any of those reflections (mainly lateral). The lack of lateral reflections can only be partly compensated for by ceiling reflections (most of the fan-shaped halls indeed have a relatively low ceiling and consequently too small an acoustic volume to guarantee an appropriate late reverberation). This absence of lateral reflections results in a weak subjective sense of envelopment.

Some of the more recent halls still adopt a general fan-shape. The use of such rooms confirms that the shape is detrimental to the acoustics and that these halls can only provide acceptable results if some appropriate reflectors are carefully installed within the volume of the hall to completely "break up" the fan-shape.

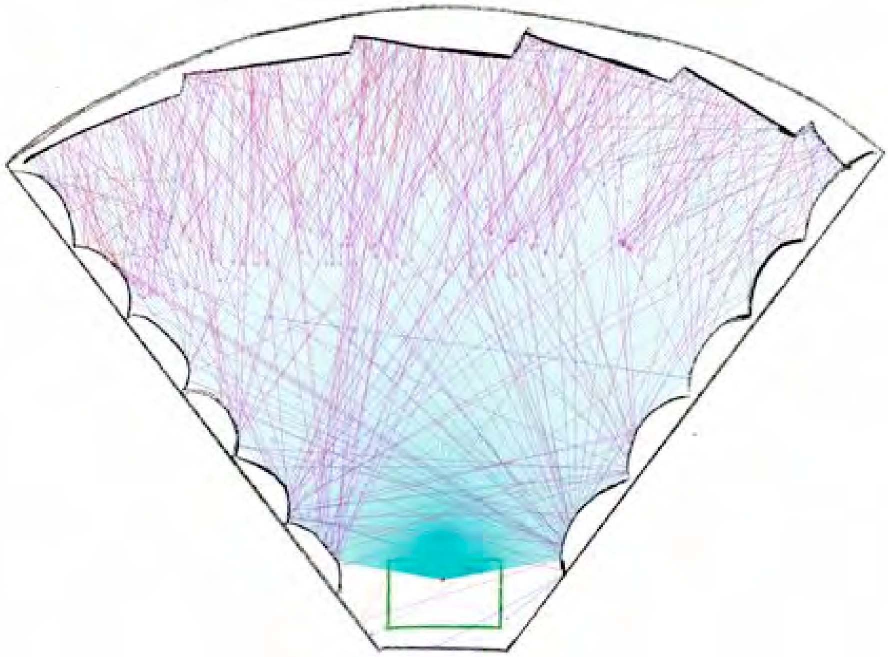
**Example of fan-shaped hall**

*The advantage of such shape is the maximisation of the capacity for a relatively short distance to the back of the stage while conserving an acceptable angle of view.*

**The acoustic effect of the fan-shape: simulation of the two-dimensional ray trajectories.**



*The reflections of the lateral walls – if any – are directed toward the back of the room while the front and middle areas do not benefit from any of those reflections.*



*The lack of lateral reflections can only be partly compensated for by having acoustic reflectors on the walls but also on the ceiling.*

There exists another type of hall, derived from the fan-shape, called the "reverse fan-shape hall". It is more an extension or optimisation of the shoebox shape in which the lateral walls are not perfectly parallel to each other but create a room which is wider at the front than it is at the back. The advantage of such a room is that the reflections of the lateral walls become more efficient at the back of the room. For a rectangular shoebox, the reflections on the rear end of the lateral walls do not reach the middle area of the room. By narrowing the back of the room, these reflections can be orientated toward the listeners in the middle area. The reflections are therefore being reinforced in the back of the room and for the entire audience.

## 1.6. The multi-purpose hall

The client has strongly expressed his wish and need for an auditorium that is more open than the classical model inherited from the end of the 19th century. The hall must particularly favour flexibility between the areas dedicated to the musicians and those for the audience.

The notion of multi-purpose uses for a hall has been around for a very long time (e.g. ball rooms in castles in which concerts were held and that precede the current concept of concert halls) but has only been clearly expressed during the first half of the 20th century and has not found adapted solutions until the end of the 20th century.

Until the 1950s, being asked for a multi-purpose room - which, for example, could host concerts and operas - acousticians used to look for a compromise between the various criteria. A multi-purpose hall at that time was "static" and without acoustic variability, with a reverberation time on the long side for operas and (far) too short for classical music concerts.

Musicians and public have, unanimously, judged these halls as unacceptable acoustically. The acoustician, architect and theatre consultant had to come up with concepts to adapt the acoustics of the hall to the different representations. We now know that to adequately adapt a hall, one must:

- Introduce variability in the *acoustics* of the room. This variability must allow for more than a simple change of reverberation time (by using acoustic curtains or other absorbing material, or by adding artificial reverberation via an electronic system). The criteria to adapt are the acoustic volume, the loudness, the lateral energy and potentially the spectral balance and/or orchestral balance;

- Introduce flexibility in the *architecture* of the room. In some cases, these modifications can be minor, in others cases, they will have to be major. The simple reason for that is that each performance is associated with a particular set of needs and often a different relationship between the audience and the artists. To address this issue correctly, one must also respect the expectations of the public that also vary with the type of performance.

During the last decades, architects, theatre consultants and acousticians have suggested a vast list of possible solutions:

- Acoustic curtains in horizontal operation (often under the lateral balconies, in front of the walls of the halls) or in vertical operation (often coming down from the ceiling, either along the walls, behind the lighting bridges, or in the middle of the ceiling, directly above the audience);

- Ceiling with variable height, to obtain a variable acoustic volume depending on the type of acoustics desired; sometimes by closing off a balcony, sometimes by simply modifying the acoustic volume while keeping the total number of spectators constant;

- Variation of the acoustic volume by moving wall elements or by closing off part of the room volume;

- Variation of volume by addition of reverberation chambers. These chambers add volume that can be coupled into the main acoustic volume of the hall;

- Variation of the acoustic coupling between the volume of the hall (including the musicians and public) and a secondary volume (located behind the acoustic reflectors and often non visible) by tuning the acoustic reflectors or the opening area between the two volumes;

- Removing part of the stalls seating or the entire stalls seating area to install a flat ground for concerts with a standing audience, exhibitions or other types of activities;

- Increase or decrease of the stage area: either at the front by adding one or several stage elements or at the back by removing part of the choir and public seating;

- For operas and theatres, the most well known mechanism to adapt the hall to symphonic music is the installation of a concert shell on stage, potentially combined with front stage elements. These projects often integrate one or several orchestra pit lifts to seat a large part of the orchestra in front of the proscenium.

Other proposed solutions have pushed the boundaries of variability and flexibility, in particular in opera houses and theatres:

- Mobile proscenium (in halls with a flytower): in multi-purpose halls where the opening of the proscenium needs to be widened during concerts of classical music. The opening of the proscenium can be wider than 20m, which is wider than a concert stage;

- Mobile changing rooms to accompany the shift from a proscenium opening of 12 to 14m to a non-existing frame or to a frame opening of 20m. In some cases, these stacked changing rooms can rotate, in other cases they can be moved laterally, or both movements can be combined;

- Mobile choir balconies, partial or total. The mobility of a few rows of the choir leads to a flexibility of the size and location of the orchestra, and a variation of the capacity of the choir (or audience) behind the orchestra. When the entire choir can be removed, it is possible to place the back of a concert hall stage in a traditional flytower;

- Mobile choir towers (also for the audience): these typically have two or three levels, with an internal staircase integrated at the back, on wheels or air cushions. They are movable on stage similar to the elements of an orchestra shell.

Most of the halls that have pushed the boundaries of variable acoustics and theatrical/acoustical/architectural flexibility are rectangular. There is a good practical reason for that: the displacements of objects are simpler to imagine in a simple rectangular geometry. At the same time, it is interesting to note that for other existing hall shapes (e.g. vineyard, early reflection design etc.) elements of acoustic flexibility have rarely been integrated despite similar needs.
One of the goals of the Philharmonie of Paris is to integrate elements offering similar acoustic flexibility to what has been achieved with shoeboxes, but in a freer hall shape.

## 1.7. Capacity of the room

Part of today's repertoire of classical symphonic concerts has been composed for halls of smaller size and less capacity than that of current concert halls. To give but one example, the Hanover Square in London, for which Haydn wrote his last symphonies, has 700 seats and was then considered a large concert hall. Another part of the common classical symphonic repertoire has been composed during the 19th century and at the beginning of the 20th century for concert halls with 1000 to 2000 seats. The comfort standards of that time allowed for an inter-row distance being much smaller than the standard set by Philharmonie de Paris. These halls had a smaller occupied surface area and a smaller acoustic volume.

A parallel development to that of the concert halls getting bigger is that musical instruments also evolved, and particularly their acoustic power. This is the case for almost all instruments: strings (development of metal strings, different means of adjustment etc.), pianos (evolution of the harpsichord, via the pianoforte, to the grand piano, with a metal frame allowing more tension in the strings), brass instruments etc. In terms of acoustic power, the most remarkable progress occurred for the brass and percussion instruments, with their power often causing problems with the orchestral balance.. It is therefore not necessary to “amplify” these instruments using nearby reflectors. On the contrary, the design of the hall must therefore take this into consideration, so as to avoid excessive power and efficient projection of these instruments that are typically located at the back of the stage (close to reflective surfaces).

Today, acoustic design must consider three different capacities for symphonic concert halls:

- Between 1300 (or less) and 1500 seats;
- Between 1500 and 2000 seats;
- More than 2000 seats.

### 1.7.1. Rooms with less than 1500 seats

One needs to know that the sound level of a symphony orchestra does not depend on the number of listeners. The hall, and above all its acoustic volume, must therefore be designed in view of sound levels and acoustic conditions relating to the orchestra, rather than paying too much attention to the number of listeners. For rooms with a capacity of less than 1500 seats, the volume per listener is therefore significant and increases further as the seat count decreases. Variable or fixed additional absorption will compensate for the smaller seat count.

Having sufficient acoustic volume and carefully planned acoustic absorption, it is possible to avoid saturation of the hall for large orchestras.

### 1.7.2. Rooms with 1500 to 2000 seats

For halls with 1500 to 1800 seats, and even up to 2000 seats, the loudness of a symphonic orchestra and the number of occupied seats are in balance with each other. As mentioned above, most of today’s symphonic repertoire (romantic and modern) has been composed for halls of this capacity. In these halls, the acoustic power of a symphonic orchestra generates the loudness corresponding to the expectations and subjective needs of the audience.

However, many criteria and elements are necessary to ensure an excellent acoustic quality. To give a few examples, it needs to be ensured that the musical definition is satisfactory at all seats (corresponding to the clarity and “intelligibility” of the instruments and musical phrasing). All listeners are nowadays used to listen to recordings on the radio or on CD (with microphones relatively close to the sources, allowing for an excellent musical definition). To a certain degree, the acoustics of a contemporary concert hall must meet this expectation. Good aural envelopment must be achieved by means of multiple and strong lateral reflections, as well as an omni-directional (diffuse) and sufficiently strong late sound field. The orchestral and spectral balance must be optimised, good listening comfort amongst the musicians must be achieved and finally, audible “flutter echoes” between parallel walls must be avoided.

The case is more delicate for chamber music and recitals for which the acoustic power of the ensembles is, a priori, not adapted and insufficient for this number of listeners. To obtain an excellent acoustic for this type of concerts, the hall must provide more acoustics reflections to “simulate” a room of smaller size (see also the next paragraph).

### 1.7.3. Rooms with more than 2000 seats

Halls with more than 2000 seats present a double challenge. Firstly, the sound level in the room needs to be maximised – simply because the acoustic energy delivered by a symphonic orchestra (which is only flexible to a small degree) is limited. The human ear and perception are very sensitive to the acoustic loudness and if the latter is too small, the sense of envelopment and the feeling of taking part in the performance will be lost. Secondly, increasing the number of listeners results in increasing the dimensions of the room and therefore pushes the reflective boundaries further away from the sources, making them less efficient. Even more important is that the time delay of the reflections (with respect to the direct sound) is increased by the increasing dimensions of the hall: if the distance to the reflective surfaces exceeds a given value, the human ear won't integrate the acoustic energy of these reflections together with the direct sound. These reflections can then not be considered to be early reflections and there will be a lack of early acoustic energy. In addition, the echo limit, which is approximately 100ms and corresponds to an additional path length of 17m (or a difference of path length between the direct sound and reflection of approximately 30m), shows that there is a real risk of echoes occurring in halls with more than 2000 seats.

For large halls, one needs to subdivide the room and/or locate reflective surfaces closer to the musicians and/or the audience than to the walls of the room.

One can, for example, install one or more reflectors above the musicians and the first rows of the stalls seating area, where the head height to the ceiling is usually greater and where the listeners are further located from the walls of the room. This would increase the listening comfort amongst the musicians and direct acoustic reflections towards the first rows of the audience. Two main options exist for these reflectors:

- One large acoustic reflector with a surface area of minimum $200m^2$ (area of the stage or more), often called "canopy",
- A set of smaller reflectors (often called a "cluster") with a minimum total surface area of $150m^2$ covering a surface area of minimum $250m^2$.

For a hall dedicated to symphony orchestras, with a well-established and limited programme, using a *fixed* large reflector (or cluster) is possible. However, for a hall with a diverse repertoire, stretching from recitals and chamber music to symphony orchestras, it is imperative for this reflector (or this cluster) to be variable in height and potentially in pitch[1].

This or these reflectors must provide a good listening comfort amongst the musicians and produce efficient early reflections for the listeners seated close to the stage, facing the orchestra but also to the sides and back of the stage (the latter also applies to the case of an orchestra with a choir behind). It is therefore a question of combining good listening comfort for the audience and good mutual hearing conditions between the choir and the musicians on stage.

[1] Pitch or slope (angle with the azimuth).

# CHAPTER 2. INFLUENCE OF ACOUSTIC REQUIREMENTS ON THE ARCHITECTURAL CONCEPT OF THE ROOM

This chapter is intended for the Architect and the Acousticians. The principal acoustic criteria are deliberately described in architectural terms. We have done the best we could in order to achieve a description that would be clear to the design team. The goal was to provide a toolbox fixing the constraint within which the designers can develop their concepts with creativity.
At the end of the chapter two tables summarise the acoustic-related architectural criteria and the specifically acoustic criteria for the project and more details are given in chapter 3.
The aim for the Philharmonie de Paris auditorium is to create an acoustic that combines great clarity and therefore a good definition and a good presence of the sources (especially considering the large seat count) with high reverberation and therefore a significant acoustic presence of the late resonance of the room. Furthermore, the resonance and reverberation of the room have to be variable so that the acoustics can be changed using different acoustic elements. This entire chapter is aimed at leading to a double optimisation of the early and late responses of the room.

For an architecturally "enveloping" concert hall, two further acoustic challenges have to be fulfilled. First – especially as the lateral walls are set farther than usual – it needs to be ensured that an adequate amount of both early and late reflections reach the ears of the listeners from a lateral direction, thus creating a good feeling of space and envelopment. Secondly, because the audience will be surrounding the stage, the distribution of the sound has to be made homogeneous so that all instruments (including those with a high directivity such as human voice) can be heard equally in the audience.

## 2.1. The room shape

In plan, no specific room shape is required and all freedom is leaved to the designers.
However, problematic shapes (see chapter 1) such as a perfect circle, an ellipse, or an excessive fan shape are to be avoided.

The goal of this document – and of the studies that led to it – is to give the Architect maximum freedom regarding the shape of the room, especially in plan, while respecting the request of an architecturally enveloping room and a close relationship between the audience and the musicians. Obviously, even if the shape of the room in plan is "free", it is necessary to ensure a suitable acoustic response, taking into account the large capacity of the hall. To do so, it will be necessary to design a set of acoustic reflectors on the walls or on the ceiling that will allow the achievement of the criteria prescribed in this programme.

## 2.2. The acoustical volume of the room

It is planned that the auditorium will host performances with organ, as well as large symphony orchestras with choirs. Consequently, the maximum reverberation time required for the auditorium with full audience and when the musicians are on stage is greater than 2 seconds.
To achieve such reverberation time, the volume of the room must be equal or greater to 12m$^3$ per member of the audience. The total volume of the auditorium will be between 28,000 and 32,000 cubic metres.
It is important to note that the acoustic reflector will have to be set within this acoustic volume. These reflectors undoubtedly include some above the stage, and some might also be somewhere else in the room. The resulting total acoustic volume of around 30,000 cubic metres is therefore not a unique architectural volume.

It is entirely acceptable from an acoustic point of view to design partially coupled volumes in the room, meaning an internal acoustic volume (including the stage, the musicians and the audience) surrounded by acoustic reflectors. Behind these reflectors will be one or several external volumes, which will be part of the total volume of the room but will be only partially visible to the audience. One of these external volumes can be the volume located above the reflectors above stage. In the same approach, other volumes could be set behind other reflectors in the room. It is not necessary to close off the exterior volumes from the interior one: a tuning and a flexibility of the coupling area between these internal and external volumes could be an interesting solution both architecturally and acoustically. Furthermore, it is suggested that elements of variable absorption be located both within the internal volume (making them visible to the audience and very "visible" to sound) and the external ones (making them less visible to the audience).

The diversity of the repertoire planned for the Philharmonie de Paris Auditorium suggests that a flexible coupling of the volumes – or at least a spatial variability – will be valuable in order to optimise and tune the acoustics of the room.

## 2.3. Reflecting surfaces – including within the room volume

A new architectural criterion has been specifically developed for the Philharmonie de Paris project. It is aiming at correlating as simply as possible a given architectural shape to its acoustic efficiency in terms of early reflection: that is to say the aptitude of the room to transfer sound energy towards the musicians and the audience in an early way.
It shall be called the early acoustic efficiency and can be determined directly from the architectural drawings. To do so, one will proceed following these steps:

- First, one needs to establish a list of all surfaces within the room located 15 meters or less from the musicians on stage and/or from a part of the audience, and the orientation of which favour the reflections towards the audience.
- This list is then increased by the surfaces located 15 meters or less from the sound source on stage, and the orientation of which favour the reflections towards the stage.
- For each of these listed surfaces (that can be referred to as *efficient surfaces*), its area S [$m^2$] is measured from the plans and sections.
- The early acoustic efficiency (in $m^2$) is finally obtained by calculating the sum of each of these surface area S

The principle of this efficiency is simple: the larger quantity of judiciously oriented surfaces located close to the sources or the audience, the greater the clarity and the presence of the sources.

Considering things in more detail, a higher amount of sound energy actually reaches the surfaces located close to the sources. Consequently, for a more accurate calculation of this criterion, another possibility is to follow the procedure bellow:

- For each of the surfaces in the earlier list, one needs to measure both its area S [$m^2$] and the distance d [m] of its centre to a sound source located in the middle of the stage.
- For each of the efficient surfaces, the factor $S / (16d^2)$ is representative of the fraction of energy produced on stage that reaches it. This factor is obtained through approximations on solid angles, such as $S << d^2$.
- Whenever this factor is greater than 0.03 (or 3%) for an individual surface, its value will be set to the maximum of 3%.
- The early acoustic efficiency (in %) is finally obtained by calculating the sum of the factors $S / (16d^2)$ for each of the efficient surfaces.

This criterion, in its two versions, as already been calculated for a number of existing concert halls. This analysis has shown that early acoustic efficiency superior or equal to 1400 square metres (500 square metres of which are less than 15 metres from the stage) and 24% is optimal for symphony concerts. With smaller values the sources sound distant, the clarity and attention of the listener are also diminished. With higher values, the sound becomes too direct and the reverberance and the acoustic presence of the room are lacking. In addition, it has to be ensured that the stage and each part of the audience are covered by at least one or two (or ideally more) of the listed acoustically efficient surfaces.

When calculating that early acoustic efficiency the following surfaces will have to be considered:

- The acoustic reflectors suspended from the ceiling above the stage, or within the volume of the room.
- The balcony fronts, when they are efficient in the way explained above.
- The portions of the walls that are efficient acoustically. Those located behind an audience are not to be considered.
- The balcony soffits, when they generate early reflections towards the stage or the audience. These reflections may be of first order or of second order (orientation of the sound toward the stage or the audience after two successive reflections: one on the balcony soffit and one on a wall or a downstand located under this balcony).
- The ceiling of the room when part of the audience is less than 15 metres from the ceiling, and only the part of it that is efficient in the meaning defined earlier.

## 2.4. Acoustic diffusion, lateral energy and envelopment

First, diffusion will have to be generated by roughness on the reflective surfaces in the room, especially at frequencies above 2 kHz (corresponding to unevenness around 50 mm deep), to multiply the number of acoustic reflections and break the "mirror effect" of too smooth or too large reflecting surfaces. As an example, an important diffusion can be obtained through convex surfaces that spread acoustic reflections on a wider area than plan surfaces.

Then, one of the main acoustical challenges for an architecturally "enveloping" room is to achieve a homogeneous distribution of the sound in all parts of the room. Even though some instruments such as the human voice are highly directive towards the front, they have to be correctly audible from a seat located behind the stage. Therefore, reflections will have to be generated to send behind the stage and on the sides a part of the sound produced towards the front. The acoustic reflectors will have to be designed to meet the needs of directional diversity of the reflections: sounds emitted in all directions should be redistributed towards all parts of the audience.

Concerning subjective acoustic envelopment, lateral reflections are necessary and will have to be provided in all parts of the audience, even in an "enveloping" concert hall where the notion of laterality depends on the orientation of the seating. It should therefore be taken into account that a reflection which is lateral for seats in front or behind the stage can become frontal for seats at the sides of the stage.

Two comments on the envelopment have to be stated. First, scientific and comparative studies of existing concert halls have shown that the perception of acoustic envelopment is highly correlated to the subjective preference of the audience. Therefore great attention will have to be given to subjective envelopment and the correlated objective parameters (LF and IACC).
Secondly, it is indeed difficult to obtain a good fraction of lateral energy in enveloping rooms: audience surrounding the stage sets the lateral walls farther, which results in weaker lateral reflections. Even in Berlin Philharmonie – which is considered as an excellent concert hall – the feeling of acoustic envelopment is slightly lacking, especially at the seats on the room's axis, located farther from the walls. For the Philharmonie de Paris auditorium, a good optimisation of acoustic envelopment is expected from the designers.

## 2.5. Balance of the orchestra, design of the stage and of its surroundings

In a concert hall the stage is one of the key elements, both for its necessary flexibility and detailed design and for its acoustic environment.
To ensure a good acoustic occurrence of the orchestra and to create the best conditions for ensemble, the stage must not be too vast and certainly not too wide.
A maximum width of 19 metres in front of the stage is suggested.

The lateral walls of the stage must not be parallel in order to avoid flutter echoes and standing waves. In order to improve acoustic projection from the stage towards the main part of the audience located in front of the stage, a narrowing of ±5 degrees towards the rear is required.

As indicated in the architectural brief, an open corridor about 1.5 metres wide is required at the sides of the stage. This space could actually be below some parts of the audience or some acoustic reflectors. This corridor enables to move the walls a bit further away from the musicians – as they usually do not like playing to close to a wall. This corridor also gives a good opportunity to integrate an acoustic reflector relatively close and slightly above the stage.

Concerning the depth of the stage, the architectural brief requires a fixed position for the conductor. There is consequently no movable apron stage and the extension of the stage depending on the size of the orchestra will have to be done towards the back.

One or several acoustic reflectors will have to be installed above the stage and the front part or the totality of the parterre. They will need to be variable in height between approximately 8 and 16 metres from the stage level and should cover a wide area (refer to chapters 3.3 and 3.7). A relatively large number of theatre technical equipment will have to be integrated in this acoustic ceiling with no loss of acoustic efficiency. Therefore, it will need to be designed though close collaboration of the architect, the theatre consultants and the acoustician. For classical concerts, it can be useful to integrate the basic stage lighting equipment in this reflector or set of reflectors.

Generally, the stage has to be surrounded by reflecting surfaces at adapted distances so that the sound is directed and projected towards all listening areas, including seats in the centre of the room near the stage (that are usually relatively far from all reflective walls), seats behind the stage and at its sides, as well as the stage itself. The surfaces close to the stage become very important for rooms with enveloping architectural shape since the lateral walls are relatively far and the different parts of the audience are located with very diverse angles from the sources.

In order to avoid plate resonance's and bass absorption these reflecting surfaces will have to be sufficiently massive. To increase the high frequency diffusion some of these surfaces might need to be treated with a roughness a few centimetres deep.

## 2.6. Acoustic variability

To meet the objective of a great acoustic variability for the room, a significant amount of acoustic variable absorption will have to be considered in the design (such as movable heavy acoustic curtains or any other solution allowing a variation of the total acoustic absorption in the room). The exact required amount of such features will depend on the volume of the room and the locations of these absorbing elements, although in any case a minimum of 1200 square metres of variable absorbing surfaces is required. Other elements might be necessary in order to tune the bass frequency response, especially for amplified events.

This criterion will have to include some mobile elements of acoustic absorption surrounding the stage, some in the vicinity of the sources and/or audience (for a variability of the early energy) and some located relatively far from the sources and audience, and less visible to the audience (for a variability of the late energy).

A concept allowing an acoustic variability by moving architectural features such as reflectors or walls or other reflective surfaces is requested. This architectural variability could be designed in order to provide a judicious variability of the useful reflecting surfaces, and thus make it possible to acoustically (and visually) adapt the concert hall to the various types of events.

As detailed in chapter 2.7, adaptability of the acoustics on stage will also have to be planned to fit the different sizes of the musical ensembles and the different types of music.

Two further comments: first, some of the mobile absorbing elements will be used and made visible in the room very often, and the configuration with the maximum reverberation time and therefore without any absorption will not necessarily be the most frequently used set up for the room. Secondly, for amplified music performances, musicians often ask that dark velvet boxes be installed behind them and on the sides of the stage for light and acoustic absorption reasons.

## 2.7. Ceiling above the stage

The large seat count of the Philharmonie de Paris concert hall implies that its acoustic volume will have to be large in order to reach the desired acoustic quality; and therefore that the ceiling will be quite high. Also for a concert hall of enveloping shape it is very likely that the ceiling height will be more important in the middle of the room, meaning above the stage. The maximum height will certainly be greater than 20 metres.

However a ceiling height of more than 20 metres above the stage is too great to ensure good listening comfort amongst the musicians and projection towards the audience. In addition this distance of 20 meters is larger than the echo threshold. In Berlin Philharmonie for example, a suspended array of acoustic clouds are necessary to provide adequate listening conditions between the musicians.

Also, to adapt the acoustics to the different types of representation reflectors will have to be installed. And if reflectors are necessary to musicians, they are also necessary to audience seating near the stage.

Furthermore, the wide-ranging program of the future Philharmonie de Paris implies a need for variable stage acoustics, and it is therefore required that the reflectors above the stage can be movable in height. Depending on the musical works and the composition of the orchestra, the height of a large reflector will generally be between 10 and 16m above stage level, and between 8 and 14m for a reflector array. In this acoustic brief, it is requested that the reflectors above the stage can be tune between 8 and 16 m above stage level.
For amplified events and events other than classical music, as well as for organ concerts, it might be interesting to be able to set the reflectors even higher.

## 2.8. Possibilities for optimised design of the reflectors, in terms of coverage and lateral energy

This acoustic brief has already heavily suggested the need for acoustic reflectors. For these reflectors to be totally “visible” to sound, they have to be located higher than the musicians and the audience. Concerning their shape, several solutions are presented below:

- Horizontal reflectors on the ceiling. The size, shape and curvature can be diverse. These reflectors are very well exposed to sound. But their limitation lies in the fact that they do not generate lateral reflections neither balanced blending.

- Vertical reflectors such as the walls or the balcony fronts, which do create lateral reflections.

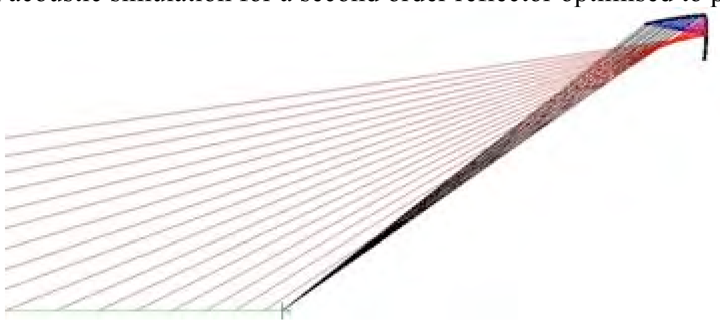
- Diagonal reflectors to combine the advantages of being exposed to the sound and generating lateral reflections. They can be hung within the space of the room.

- Balcony soffits, which also combine the advantages of being well exposed to sound and generating lateral reflections. This solution is used in most of the shoebox halls and can also be used in any type of room.

- "Generalised second order reflectors". The balcony soffits usually work as the combined action of the somehow horizontal soffit and the somehow vertical highest part of the wall below it. It is therefore not a single but a double reflection, usually called second order reflection. Obviously, 2nd order reflections can be adapted and generalised to other shape. And such reflections are not necessarily created by balconies: suspending a vertical and a horizontal surface within the volume of the room will create the same acoustic effect.

*Acoustic simulation of a second order reflector: black rays shape the direct wave towards the vertical surface (for clarity the paths towards the horizontal surface has not been drawn), red rays shape the reflected wave (after two successive reflections). The green line shows the area covered with reflections.*

- "Optimised reflectors of the second order". In a second order reflector, it is possible to change the curvature and angles of both the vertical and horizontal surfaces. This opens multiple possibilities for setting the directivity of the reflections and the coverage. The picture below shows the result of an acoustic simulation for a second order reflector optimised to provide a wider coverage area.



*Acoustic simulation of a second order reflector: black rays shape the direct wave towards the vertical curved surface; red rays shape the reflected wave (after two successive reflections). The green line shows the area covered with reflections.*

## 2.9. Audience distribution

In the architectural brief it is suggested that the parts of the room that are not occupied by the audience could be "turned off". The solution suggested in the architectural brief is a simple light effect to keep these unoccupied areas in the dark.

Concerning the acoustics, the following aspects could be considered:

- First, it is possible to use these unoccupied areas as reverberation areas by using seats with little absorption so that when the audience is smaller the maximum reverberation time of the room will be increased which can be ideal for vocal music concerts or more generally when longer RT is profitable. If this longer RT is not wanted, variable acoustics features could be used to dampen these areas. However, for amplified events repetitions it will be necessary to plan for a sufficient amount of integrated variable absorption.
- It was stressed in the architectural brief that the possibility of closing the unoccupied zones with curtains or hard surfaces is not desirable. The intended use of the auditorium includes only very rare recitals or chamber music concerts. Consequently, an optimisation of the acoustics specifically for such performances is not required. However, for concerts with a lesser audience it could be interesting to partially close off the visible volume of the room using acoustic reflectors to create greater intimacy both acoustic and visual.
- Since the room will have to be an enveloping room, there will be a high number of seats on the side and behind the orchestra. These seats can be great both for the audience (proximity to the musicians, feeling of being involved in the event, frontal view of the conductor) and the musicians that found themselves surrounded by the audience. Ideally these seats shall always be occupied and particular attention will have to be paid to their acoustic quality.

## 2.10. Integration of the organ

The integration of the organ in the concert hall has impacts on the morphology and architecture as well as the acoustics of the room.

### 2.10.1. Impact on the dimensions, retained space

A traditional organ is a complex piece of equipment composed of one or two thousands of tubes organised in several rows. Tubes for lower tones can reach between 5 and 6 metres in height for a 16 feet organ, and much more for a 32 feet one. It is also a complex mechanical system sitting on a complex wood structure, possibly reinforced with steel.

For a concert hall of such volume, the organ can typically be 12 to 15 metres wide, up to 10 metres high and 6 metres deep, occupying a surface between 40 and 80 square metres.
The tubes of the organ must not be too close to each other so that their resonances are freely allowed. An access for the musician will also have to be planned for, as well as access inside the organ to tune and maintain it.

### 2.10.2. Choosing the location of the organ

Considering the enveloping shape of the Philharmonie de Paris concert hall, it seems difficult to impose a location for the organ in the room. However, the following constraints must be considered when choosing the location of the organ:

- The entire organ must be visible – including the top of the tubes – for most of the audience.
- The position must allow for good balance between orchestra and organ and consistency of sound, for the audience as well as the orchestra director.
- The position must allow for good acoustic quality of the instrument and a comfortable position for the musician playing the instrument. Generally organ players do not favour having the keyboard moved onto the stage (even if this possibility is planed and required for the project).
- The smallest tubes (high frequencies) are acoustically very directive and acoustic reflections from close surfaces are needed to create a good distribution of high frequencies.
- The height of the organ has quite important consequences:
  - The vents of the most powerful tubes must not be at the same height as the choir.

- Also a good balance between the high and the low frequencies will have to be achieved at the player's position.

Often the installation of an organ leads to an increase in the ceiling height. However, this height must remain compatible with the necessity of the reflectors close to the orchestra and reflecting towards the stage.

With acoustic reflectors above stage, it is even more complicated to find a good position for the organ, as it should stay fully visible for most of the audience. It is quite recurrent that the organ is "visually cut" in rooms with reflectors above stage.

### 2.10.3. Impact on the acoustics of the room

The volume of the room must be adjusted so that in full configuration for symphony with choir and full audience the RT remains greater than 2 seconds at mid frequencies. In addition, the organ is a part of the acoustic treatment of the concert hall. The absorbing and diffusing characteristic of the organ must be considered when choosing the location of the organ in the room.

## 2.11. Background noise criteria

The absence of any noise during the representation is an integral part of the acoustic quality of the room.

The background noise shall be extremely low, at the limit of the threshold of hearing, both for the concerts with an audience and recording situations.

The corresponding objective criteria are "Noise Rating" (NR) and the pressure level expressed in dB (A). For the main concert hall of the Philharmonie de Paris, the required noise-rating criterion should be NR10, and the absolute level of 15 dBA.

## 2.12. Sound insulation

In order to achieve an almost absolute quality of silence, sound insulation from the exterior as well as from the potentially noisy rooms in the building will have to be excellent, and in correspondence with the background noise criteria of NR10 and 15 dBA.

In order to isolate the room from the airborne noise from outside as well as inside the building it will probably be necessary to envelope the room with a double leaf structure. Two massive walls will always separate the interior of the concert hall from the outside or the potentially noisy rooms.

Concerning the vibration isolation, including from the rehearsal rooms and plant rooms, structural isolation using acoustic joints or complete non-contact type of isolation is suggested. As indicated earlier, the acoustic insulation concept should in any case be based on the background noise level requirements. Concerning the vibration isolation from outside sources, please refer to the vibration study report.

## 2.13. Summary table of the major architectural/acoustical criteria

| Architectural Parameter | Requirement |
|---|---|
| Volume per person | Ideal: between 12m$^3$ and 13m$^3$.<br>Acceptable: between 11m$^3$ and 14m$^3$. |
| Total volume | Approx. 30000m$^3$ (between 28000 and 32000m$^3$) to obtain 12 to 13m$^3$ per person in the audience and for 2400 seats. |
| Reflective surfaces | 1400m$^2$ including 500m$^2$ close to the musicians (less than 15m from a point of the stage). |
| Height of the auditorium | The height will be chosen by the design team to obtain the appropriate volume of 30000m$^3$.<br>The ceiling will not necessarily be flat. It is understood and considered acceptable that the total height (omitting the acoustic reflectors) above the stage can be greater than 20m. |
| Height of the reflectors above stage | Required variability: between 10 and 16m for a continuous large reflector (canopy) and 8 to 14m for a set of smaller acoustic reflectors |
| Variable acoustic absorption (curtains or other elements) | More than 1200m$^2$ of absorbing material is required, which shall be exposed to sound or removed with the use of motorised or mechanised machinery. |

## 2.14. Summary table of chosen acoustical criteria

| Acoustical | Value at mid-frequencies |
|---|---|
| Reverberation Time (RT) | Mean between 2.2 and 2.3s with all variable acoustic absorption retracted (*fully occupied with orchestra on stage*)<br>Mean between 1.4 and 1.6s with all variable acoustic absorption in place (*empty auditorium*)<br>Mean between 1.2 and 1.4s with all variable acoustic absorption in place (*full house, empty stage*) |
| G, without audience | Mean between 3 and 6dB.<br>The variation with respect to the position of the source and receiver ($\Delta G$) must be ±3dB.<br>Acoustic variability (mean of G using the variable acoustic features) must be greater than 2dB. |
| G80, without audience | Mean between -2 and +2dB.<br>Required variability: >3dB. |
| G[80ms, ∞], without audience | Mean between 0 and 4dB.<br>Required variability: >1.5dB |
| C80, without audience | Mean between -3 and 0dB.<br>Required variability: >2dB |
| LF, without audience | Mean > 0.16,<br>LF >0.15 for at least 80% of the seats. |
| 1-IACC, without audience | Mean >0.55,<br>1 – IACC >0.5 for at least 80% of the seats. |
| Bass ratio, without audience | Between 1.1 and 1.3. |
| Treble ratio, without audience | Between 0.9 and 1.0 at 2kHz.<br>Between 0.75 and 0.85 at 4kHz. |
| ST1, without audience | Required variability: >3dB.<br>Possibility to reach values ≤ -16dB<br>Possibility to reach values ≥ -14dB.<br>Variation across the stage: < 2dB with respect to the mean value. |
| Noise rating | < NR10 and 15dB(A) |
| Tolerances | Corresponding to the threshold of hearing (5-10% for the RT, usually 1dB for the other criteria, 5% for the LF and 1-IACC). |

# CHAPTER 3.
# SUBJECTIVE PARAMETERS AND OBJECTIVE CRITERIA

The client's stated wish is for an enveloping room with a relatively important number of seats located behind stage as well as on its sides. As explained in the architectural brief it is also required that the location of the stage be, to some extend, variable: the stage shall be able to move toward the back of the room, in particular for world music and amplified music.

The acoustical design for the principal use of the room as an auditorium for symphonic orchestra, is however to be carried out for the central location of the stage.

The objective criteria values required and presented in the following are all to be considered assuming that the stage is in its central location ("first stage area for the symphonic orchestra"). The motion of the stage toward the back of the room ("secondary stage area") can – and must – go with a variation in the acoustic quality, more adapted to the amplified music concerts.

The acoustic criteria listed in the previous table and explained in the following are also to be considered in the analysis of simulations data, which are required from the design phase in order to demonstrate that the design of the auditorium meets these criteria.

In room acoustics, one often distinguishes the "subjective parameters" and the "objective criteria". The subjective parameters describe the perception of the various qualitative characteristics of the room acoustics. The objective criteria are the parameters calculated from the objective measures of the impulse response of the room and describe the acoustic response of the room between a source and a receiver. The objective criteria are defined to quantify the subjective characteristics of the room. Several scientific studies have derived relationships and correlation between these different criteria in order to shape a consistent correspondence between objective criteria and subjective parameters. A priori, these relationships can be applied to any room shape and consequently, can be applied to the "enveloping" room required by the client and end users.

In this chapter, the different aspects of the acoustic quality of the room will be considered, one by one, considering simultaneously the subjective and corresponding objective quantities. The exact definitions of these criteria are given in annex 2 of this document.

## 3.1. Reverberation and reverberance

The first objective criterion used to describe the acoustic quality of a concert hall is the reverberation time (RT) that measures the duration of the decay after extinction of the sound source over a dynamic range of 60dB.

The subjective parameter related to the RT is the notion of "perception of the reverberation" or reverberance. In practice, one distinguishes between the reverberation perceived during the musical phrase (running reverberance) and that perceived once the musical phrase is over (final chord reverberance). The latter is directly related to the RT of the room while the former is more related to the early decay time and often calculated over a decay of 10 or 15dB (EDT10 and EDT15).

One of the principal reasons why the RT is generally the first criterion used for the description of the acoustics of a concert hall is that it is the only criterion that does not vary (or negligibly) with the source and receiver positions. Therefore, it characterises the reverberation of the room uniquely.

The RT is directly related to the acoustic volume and the absorption area of the room. Given that the total absorption area for a concert hall is essentially made of the seated audience, the RT is directly related to the total acoustic volume or to the acoustic volume per person in the audience.

The Philharmonie de Paris brief includes the installation of an organ in the room. The room will therefore be designed accordingly for music performances with organs as well as performances with a symphonic orchestra and choirs.

Thus, the maximum RT required for this auditorium (full audience without curtains or any movable acoustic feature) is 2.3 seconds. In any case, the maximum RT of the room, fully occupied and with musicians must be greater than 2seconds.

To obtain such a maximum RT, one must plan for an acoustic volume of $12m^3$ to $13m^3$ per person of the audience and consequently a total volume of $30000m^3$ for the auditorium.

## 3.2. Loudness and acoustic power

The subjective parameter of acoustic power is related to the objective strength criterion G. This criterion measures the loudness and amplification of the room. It is defined as the ratio (in dB) of the acoustic pressure measured at a given point of the room (response of the room) to the acoustic pressure generated by an omni-directional source of similar acoustic power and measured at 10m from the source in free field conditions. This criterion is a function of the position of the source on the stage and of the position of the receiver.

For the Paris auditorium, with its capacity of more than 2000 seats, this acoustic criterion is very important for two reasons. First, the loudness G must be great even with the size of the audience considered. Secondly, the variations of G with the location of the source on the stage and of the receiver in the audience must remain small.

The human ear is very sensitive to acoustic power. Below a certain threshold, awareness is reduced and the audience does not feel as being part of the event. For a large concert hall, it is generally admitted that G must be positive (greater than 0dB for the mid-frequencies) for all seats. One generally considers that the ideal value of G is between +2dB and +8dB.

For Paris auditorium, the mean value of G (calculated over a set of representative seats which excludes the seats located within 5m from the stage) must be between +3dB and +6dB.

The spatial variations of the loudness G in the room, excluding the seats within 5m from the stage, must be less than 3dB with respect to the mean over the entire room (±3dB).

## 3.3. Early energy and presence of the source

Recent studies in psychoacoustics have demonstrated that the perception of acoustic power is more complex than the simple correlation with G or with the room amplification.

Indeed, the human ear – and the brain – differentiates the audio information into two different “data streams”. One is related to the perception of the source while the other one is related to the perception of the space. This is logic from a cognitive point of view: seated in a concert hall, one tries to get information concerning the source (and especially concerning its sound or musical message), and concerning the environment he is in. Therefore, the design shall aim at optimising independently the early response (presence of the source) and the late response (presence of the room).

The presence of the source is related to the early energy of the room response. In a large concert hall, excluding the seats that are very close of the stage (3 to 5m from the sources) between 90% and 99% of the acoustic energy comes from reflections on the walls of the room.

The human hearing system integrates the energy from the reflections into the energy of the direct sound if the reflections arrive with less than 80ms delay with respect to the direct energy. The perceptive process is indeed more complicated, but a restriction of the integration to the first 80ms constitutes a sufficient description in the context of the design of the Philharmonie de Paris.

In order to obtain a good, perceivable, presence of the sources, one needs to create an important number of reflections (using reflectors or the walls) which arrive with a shorter than 80ms delay. The number of seats required and the large volume of the room make this even more important. A delay of 80ms corresponds to a difference of 25m in the ray trajectory. Since the sound must reach the reflective surface then travel to the ears of the audience, one needs to install reflective surface close to the source and/or audience at a distance not less than 10 to 15m.

An efficient design of the reflectors that provides a sufficient acoustic energy for the early reflections is one of the most important challenges in the conception of the auditorium. Given this importance, more detailed criteria and a new architectural acoustics criterion are given in the previous chapter 2.3.

Concerning the purely acoustical criterion, the early strength G80 (defined as the ratio of the room amplification for the first 80ms of impulse response to that obtained at 10m in free field conditions for a unidirectional loudspeaker) is less universally used, but will nevertheless be used here. For the Paris auditorium, the G80 value, spatially averaged over several representative seats excluding those in the vicinity of the stage, must be between -2dB and +2dB.

Also, a negative C80 between -3dB and 0 dB (empty room) is required.

## 3.4. Late energy and presence of the room

As mentioned in the section 3.1, the perception of the final decay (end of a musical phrase) is directly related to the reverberation time. The perception of the reverberation during continuous musical phrases requires not only a sufficiently long RT but also a sufficient amount of late acoustic energy, 80ms after the direct sound reaches the audience.

For the Paris auditorium, a late G[80ms, ∞] (averaged over several seat including those below the eventual balconies) must be between 0dB and +4dB. Moreover, it is required that this criterion be homogeneous over the entire seating area. The deviation from the mean must be less than 3dB when including the seats located at the back of the room and those below the eventual balconies.

## 3.5. Lateral energy and envelopment

Scientific studies and analyses of various rooms have shown, from 1960, the importance of the spatial characteristics of the sound field. Indeed, our hearing system “prefers” receiving part of the information of the reflected energy in a lateral manner than in a direct manner or as coming from above. When the reflected energy reaches the ears from a lateral direction, each ear is submitted to a different sound field, which is perceived as a feeling of acoustic envelopment. The spatial perception is thus created and, consequently, the audience feels surrounded by the sound and feels like it is participating to the event rather than simply listening and observing it passively.

It can be said that lateral reflections (with a minimum angle of 25 degrees with respect to the trajectory of the direct sound) are more advantageous than the reflections on the ceiling – unless the latter reach the ears of the listener in a lateral manner, by mean of potential reflectors installed on the ceiling with optimised angles. The sections 2.3 and 2.4 provide more detail information on the possibilities of creating lateral reflections toward the listener, either by using the walls or the ceiling of the room.

To objectively quantify the subjective feeling of acoustic envelopment (also called the “feeling of the space”), one can either use the lateral energy fraction (LF) or the inter-aural cross correlation (IACC).

For the Philharmonie de Paris concert hall, the spatially averaged LF (over several representative seats, excluding those within 5m from the stage) must be greater than 0.15 for each of the 250, 500 and 1000Hz octave bands. The averaged LF over these three octave bands must be greater than 0.16. At least 80% of the seats must have a mean LF greater than 0.15. To avoid the false localisations, the values of LF must remain inferior to 0.30, at the exception of the seating areas close to the lateral walls.

The criterion IACC will be used in its 1-IACC form so that a greater value will correspond to a better acoustics. For Paris, a mean value of 1-IACC[E,mid] greater than 0.55 is desirable and a mean value greater than 0.50 is required. The 1-IACC[E] must, in average, remain greater than 0.50 for each of the 500, 1000 and 2000Hz octave bands. It is required that at least 80% of the seats exhibit a 1-IACC[E,mid] greater than 0.50.

## 3.6. Spectral balance and building materials

An excellent transmission of the spectrum from the stage to the listener is required. For a large room, a greater RT at low frequencies (compared to mid frequencies) is desirable. For the high frequencies, a slight decrease of both the RT and the sound level is required above 2kHz to avoid a soar and aggressive response.

The bass absorption should not be in a too large amount and should be kept in control (avoiding increased absorption by plate resonances). Therefore, the materials used for the reflective surfaces must be sufficiently dense and heavy. For the high frequencies, on top of the natural absorption in the air, an additional absorption phenomenon must be considered: either by adding a very small amount of absorbing materials effective only above 2 kHz or, and preferably, by introducing acoustic diffusion above 2 kHz which leads to a slight increase of absorption.

The corresponding acoustic criteria are expressed in terms of ratios for low and high frequencies with respect to mid frequencies, both for reverberation time and for acoustic energy. For the Philharmonie de Paris concert hall, the required values of these ratios are:

- Reverberation time at low frequencies, “bass ratio” between 1.1 and 1.3.
- Loudness (strength G) at low frequencies with respect to mid frequencies, greater than -2dB.
- Reverberation time at high frequencies, “treble ratio” (with occupied room):
    - RT(2kHz)/RT(500Hz) and RT(2kHz)/RT(1kHz) between 0.9 and 1;
    - RT(4kHz)/RT(500Hz) and RT(4kHz)/RT(1kHz) between 0.75 and 0.85.

## 3.7. Musician to musician listening capabilities

In an excellent concert hall, it is necessary that the audience is able to listen in good acoustical conditions, but it is also vital that musicians are able to listen to themselves. The listening conditions on the stage must be excellent so that the musicians can deliver the best of themselves.

There are two aspects to consider: first, each musician must be able to hear himself properly (sufficiently but not to the point that his own sound masks that of the others). Secondly, each musician must be able to hear the others on the stage properly and sufficiently, even those that seat on the other side of the stage.

The surface area occupied by a large symphonic orchestra is about 200m$^2$, roughly 18m wide and 12m deep. The distance between musicians can then vary between 1.5m (the closest musician) to more than 10m. The acoustics of the room, and especially of the stage, must allow each musician to hear the furthest musicians almost as clearly (and as loud) as his closest neighbours. To achieve such acoustics, one must create reflection paths across the stage that are uninterrupted by the musicians. This is done by using reflective surfaces located above the head of the musicians.

The most commonly used criterion to define the listening comfort between musicians on stage is the "Support Criterion" denoted ST1. The ST1 criterion compares the acoustic energy that is reflected (during the first 100ms) to the acoustic energy of the source (see Annex 2 for a more complete definition of ST1).

In the literature, the optimum value is generally accepted to be -15dB to -12dB. This is an ideal value that can be applied to the rehearsal rooms and to smaller symphonic rooms as well. This value is difficult to achieve in very large rooms. The Concertgebouw of Amsterdam exhibits a ST1 value of about -17 to -18dB that can be considered as a lower limit for ST1. The listening comfort on the stage of Concertgebouw is difficult (according to the musicians in residence and other orchestras) but remains reasonable. These values in Amsterdam can therefore be considered as minimum acceptable values. However, anything lower will be considered unacceptable.

It is important that ST1 is constant over the entire stage, and that the listening conditions are homogeneous on stage. Furthermore, a localised increase of ST1 at the back of the stage (where the brass instruments and percussions are) must imperatively be avoided. Because these instruments generate high sound levels (which increase the difficulty of listening to the others) one must avoid increasing their own feedback. If reflective surfaces are to be placed in the vicinity of such instruments, one needs to plan for a mean to cancel their effects with acoustic curtains or other absorbent materials.

Moreover, the ideal ST1 value depends highly on the size of the ensemble on stage and of the repertoire. A very large symphonic ensemble (possibly with choirs and organ) does not need a very high ST1 value while a chamber orchestra or chamber music can benefit from a higher ST1 value.

For the Philharmonie de Paris concert hall, it is required that one or more reflectors be placed above the stage to generate reflections that facilitate the listening conditions amongst the musicians. Moreover, these reflectors must be mounted so that their height can be varied to efficiently adjust the ST1 value.

The following values of ST1 are required:

- Mean over the stage of ST1 between -17dB and -13dB, with a flexibility of this mean ST1 of at least 3dB (by adjusting the reflectors hanging over the stage and by other variable acoustics features in the vicinity of the stage),
- Minimum desired height for the movable reflectors above the stage: 8m (maximum of 9m),
- Maximum desired height for the movable reflectors above the stage: 17m (minimum of 15m),
- Possibility to achieve ST1 less than -16dB.
- Possibility to achieve ST1 more than -14dB.
- Maximum acceptable variation of ST1 across the stage: ±2dB with respect to the mean value.

## 3.8. Acoustic faults to be avoided

It is obvious that any perceivable acoustic faults must be avoided (echoes, flutter echoes, individual late and audible reflections…).

However, a good reflection on the back wall toward the stage can be acoustically advantageous (if it is not perceived as an echo) as it allows the musicians to have a feedback from the room.

## 3.9. Acoustic variability

As stressed throughout the present document, the principal aim of the Philharmonie de Paris concert hall is to achieve an exceptional quality for the symphonic repertoire, when the stage is in its central position. Consequently, the criteria given in the previous sections are specific to this particular context and for this precise position of the stage.

The displacement of the stage toward the back of the room (secondary stage area) will result in variations of the acoustic quality of the room. Ideally, this quality should be more appropriate for the concerts using amplified sources.

On top of the acoustic variations generated by the displacement of the stage, since the use of the room is planned to include various types of events, it is crucial to plan for an important variability of the acoustics.

The various repertoires considered for the Philharmonie de Paris concert hall are:

- Classical symphonic concerts;

- Symphonic concerts with choirs and/or organ for which a higher reverberation (duration and level) is required;

- Organ recitals;

- Exceptionally chamber music and recitals. The acoustics must allow these concerts to take place in good condition, without requirement of a perfect adaptation;

- Contemporary music concerts with or without amplification of some sources and integration of an electro-acoustic treatment or “spatialisation”;

- Opera concerts or with choreography, for which speech intelligibility is to be considered which impose a shorter reverberation and a greater presence of the sources;

- Jazz and world music concerts, generally amplified. For these, the reverberation and presence of the room must be greatly decreased;

- Amplified music concerts. The acoustics must be acceptable for such concert without having to imitate the acoustics of a room dedicated to this use.

- Exceptional shows, both classical and amplified music, for which no criterion can be imposed. The show will have to be adapted to suit the room with all its flexibility.

The need for a variable acoustics is by now made obvious and the possibility to vary several parameters is required as follows:

- A variability of the reverberation time:
  - High end: 2.2s to 2.3s (when both room and stage are occupied),
  - Low end: 1.2s when the room is occupied (1.4s when the room is empty).

- Variability of the mean value of strength G: 2dB minimum.

- Variability of the mean value of early strength G80: 3dB minimum.

- Variability of the mean value of late strength $G[80,\infty]$: 1.5dB minimum.

- Variability of clarity C80: 2dB minimum.

Ideally, it is highly desired that the tuning of the early and late energy indicators be made as independently as possible. To obtain a good variability of the early energy, acoustics curtains (or other elements of similar effects) must be located close to the sources. The variability of the late response and clarity C80 requires the installation of variable acoustic elements far from the sources, not covering the reflectors that provide early reflections. An analysis on the distribution of the variable acoustic elements and on the flexibility of the location of the reflectors will be needed: variable absorption on the surface close to or far from the audience, in front or behind the reflectors, possibility for moving or tuning the height of the ceiling reflectors. More generally, the visibility – or invisibility – of the variable acoustic elements could have a major role in the architectural conception.

Moreover, as described earlier a variability of the acoustics on stage is required in order to acoustically adapt the venue to ensembles of various sizes and styles.